Monthly Weather Review
VOLUME 98, NUMBER 10
OCTOBER 1970

UDC 551.551.5:551.515.41:551.510.53:629.73:656.7

ATMOSPHERIC GUSTS—A REVIEW OF THE RESULTS OF SOME RECENT RESEARCH AT THE ROYAL AIRCRAFT ESTABLISHMENT

J. BURNHAM
Royal Aircraft Establishment, Bedford, England

ABSTRACT

Recent Royal Aircraft Establishment research on gusts has been particularly concerned with severe gusts and the situations in which they occur. In the stratosphere, mountain wave conditions and the vicinity of thunderstorm tops have been investigated. At lower altitudes, gusts in and near thunderstorms have also been studied, as have wind and gust effects likely to be significant during takeoff and landing. The mathematical modeling of severe gusts relevant to aircraft design is described, and the effects of pilot control activity during flight through gusts are considered briefly.

Particular emphasis has been placed on two aspects of the work: (1) the study of possible means by which severe gusts might be avoided in aircraft operations and (2) the limitations of existing mathematical models of gusts that are used in aircraft design. Suggestions are made for models that may prove to be both more accurate and more physically plausible.

1. INTRODUCTION

This is a brief account of what the Royal Aircraft Establishment (RAE) has learned from research on atmospheric gusts since Zbrożek's review (1965). The period from that time to the present has seen the consolidation of several trends that were then apparent. In particular, concern about design cases that are not primarily structural but affect handling qualities and flight control systems has increased, and greater emphasis has been placed on operational aspects. (That these are interconnected is apparent from consideration of a number of accidents and incidents that became known as the "jet upsets.") In considering the usefulness of gust research, it should be noted that results that improve the ability to predict and avoid severe gusts can be applied now to current aircraft, whereas improvements in design criteria will benefit relatively few airplanes even in 5 yr. The basic aim of recent RAE research in this field has therefore been the study of severe gusts and the situations in which they occur. This work has been done in close collaboration with the Meteorological Office and a number of overseas organizations. The material presented here is taken mainly from unpublished RAE papers.

2. SOURCES OF SEVERE GUSTS

A survey of catastrophic accidents to civil transport aircraft in which encounters with gusts played a significant part shows 20 such accidents since 1950. These are listed in table 1. Of these 20, 17 are clearly linked with thunderstorms, as probably are two others. The remaining one is the accident to a Boeing 707 near Mount Fuji, where structural failure occurred during an encounter with a severe gust on the lee side of the mountain where strong mountain waves existed.

A further source of data (unpublished) on operational encounters with severe gusts has been the U.K. Civil Aircraft Airworthiness Data Recording Programme. During the first 6.8 million n.mi. of the program, normal acceleration increments exceeding 0.6 g occurred in flight on 46 occasions. All were associated with gusts. Thirty-five percent of the cases were noted by the crew as being associated with storms, and a further 17 percent were probably so; 12 percent were noted by the crew associated with jet streams, leaving 36 percent "unknown." Many of the latter, however, occurred in areas of the world at times of the year when thunderstorms are common.

Taking the encounters as a whole, 54 percent occurred during climb or descent and 46 percent during cruise. The duration of the turbulence patches in which the encounters took place tended to be short (fig. 1); duration of half the encounters was less than 1 min.

A significant number of injuries (and occasionally deaths) occur to passengers and cabin crew during flight through turbulence, in almost all cases the unfortunate person not having been securely strapped into his seat. Reliable statistics are difficult to obtain, but it appears that many incidents are connected with storm encounters and some with gusts associated with mountain wave systems. Very few seem to be associated with clear air turbulence (CAT) in the usual sense of the term.

TABLE 1.—*Accidents to civil transport aircraft involving turbulence in which major structural failures occurred in flight**

Date	Location	Aircraft	Weather
June 1950	United States	DC 4	Line squall with thunderstorms
Jan. 1951	Natal	Dove	Dark rain cloud
Sept. 1951	Greece	DC 3	Scattered thunderstorms
Feb. 1953	Mexico	DC 6	Frontal wave with thunderstorms
May 1953	India	Comet 1	Thunderstorm
May 1953	United States	C46F	Scattered thunderstorms, accident at squall line
July 1953	Pacific	DC 6A	Extreme thunderstorm activity
Aug. 1957	Alps	Learstar 18	Cold front with severe turbulence and some thunderstorm
Dec. 1957	Argentina	DC4	Cold front with thunderstorms and severe turbulence
Mar. 1959	India	DC 3	Thunderstorm
May 1959	United States	Viscount	Cold front with large rapidly developing thunderstorms
July 1959	United States	B26C	Thunderstorm
May 1960	Argentina	C46F	Cold front. Jet stream "brought airmasses down from hills."
Sept. 1960	Elba	Viscount	Cold front with thunderstorms
July 1961	Argentina	DC 6	Cold front with scattered thunderstorms
Nov. 1961	Australia	Viscount	Thunderstorms
Feb. 1963	United States	B720B	Squall line with thunderstorms
July 1963	India	Comet 4C	Monsoon thunderstorms
Mar. 1966	Japan	B707	In lee of Mount Fuji in wave conditions
Aug. 1966	United States	BAC 111	Extensive linked thunderstorms

* Data based mainly on *World Aviation Accident Digests* published by the Curl Aviation Organization, Montreal, Canada

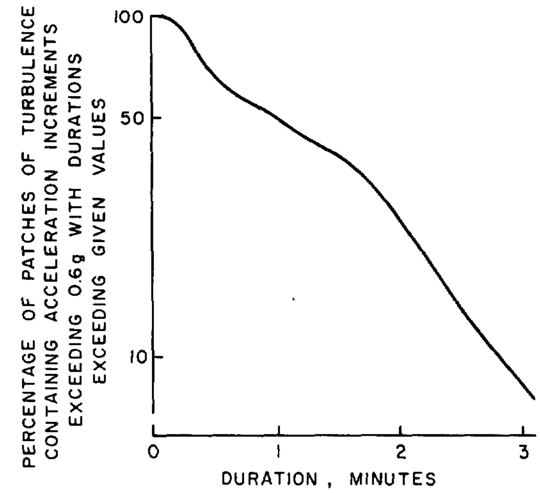

FIGURE 1.—Duration of patches of moderate and severe turbulence encountered on worldwide civil jet operations.

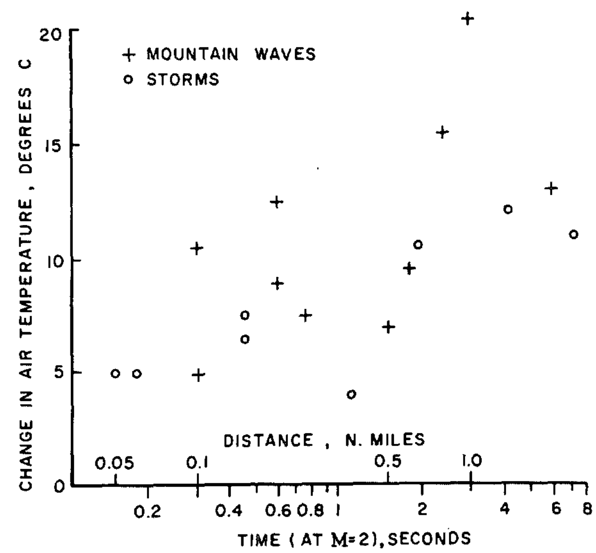

FIGURE 2.—Examples of large and rapid changes in air temperature encountered in the stratosphere.

3. GUSTS IN THE STRATOSPHERE

Operational experience at the altitudes at which SSTs (supersonic transports) will cruise is very slender. Much of the RAE gust research effort in recent years has been spent in exploring this environment, which is essentially the lower stratosphere, particularly in situations in which it is thought that severe disturbances might occur. The results of this work to date, together with those of the U.S. Air Force HICAT (high altitude clear air turbulence) program, have recently been reviewed (Burnham 1970).

Gusts large enough for their avoidance to be desirable by civil aircraft have been found (in the RAE work) in clear air near the tops of thunderstorms (up to 20 mi laterally and 10,000 ft vertically from the top of the cloud) and in association with mountain waves. One patch of severe turbulence of the latter type found at 46,000 ft contained a horizontal gust that reduced the indicated airspeed of the aircraft by 50 kt in 1 sec, a similar gust of opposite sign occurring some 20 sec later. Large and rapid changes in air temperature have been found (fig 2) in both mountain wave (fig. 3) and storm situations. Patches of marked turbulence, particularly those associated with storms, are sometimes very short (fig. 4).

The aircraft penetration of parts of thunderstorm clouds that enter the stratosphere is likely to be at least as dangerous as penetrating thunderstorms at lower altitudes, not only due to gusts but also to encounters with large hail, high concentrations of liquid water, and to possible engine malfunctions due to the intensely cold temperatures that may well exist in the storm tops (fig. 5). There is some evidence that significant gusts exist near storm top level, at somewhat greater distances from the storms than is the case at altitudes between 25,000 and 35,000 ft. The strength of the wind near and above tropopause level appears to be the controlling factor in determining their strength, lateral extent, and the height range affected, but present data are insufficient for firm numbers to be assigned to these relationships. It is clear, however, that many thunderstorms, at least in temperate latitudes, will produce no noticeable disturbances at SST cruise altitudes. Provided that the weather radar is used correctly (particularly with reference to antenna tilt) and currently recommended practices followed, it appears that thunderstorms will be rather less of a hazard to a SST during cruising flight than they are to subsonic aircraft.

It has been known for some time that, under favorable conditions, mountain and lee waves can propagate into

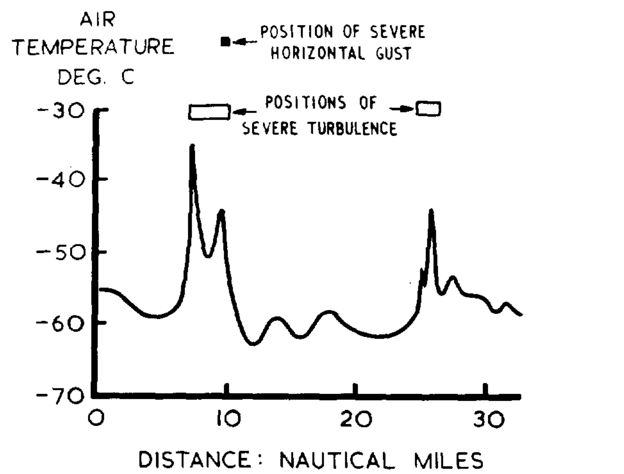

FIGURE 3.—Time history of air temperature encountered during flight through a mountain wave at an altitude of 46,000 ft.

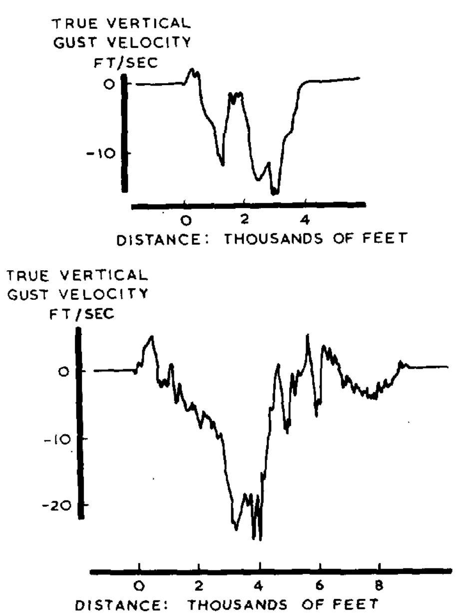

FIGURE 4.—Examples of gusts measured in clear air near thunderstorm tops.

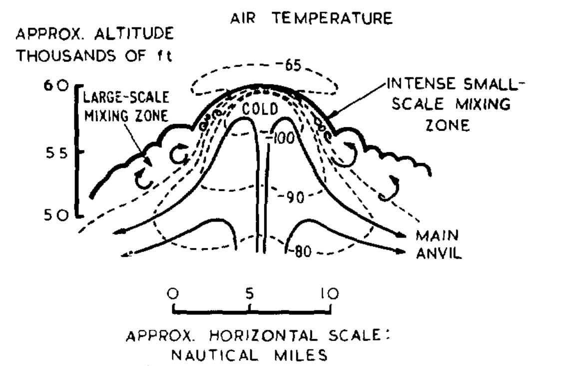

FIGURE 5.—Tentative model of a quasi-steady storm top (after Roach 1967).

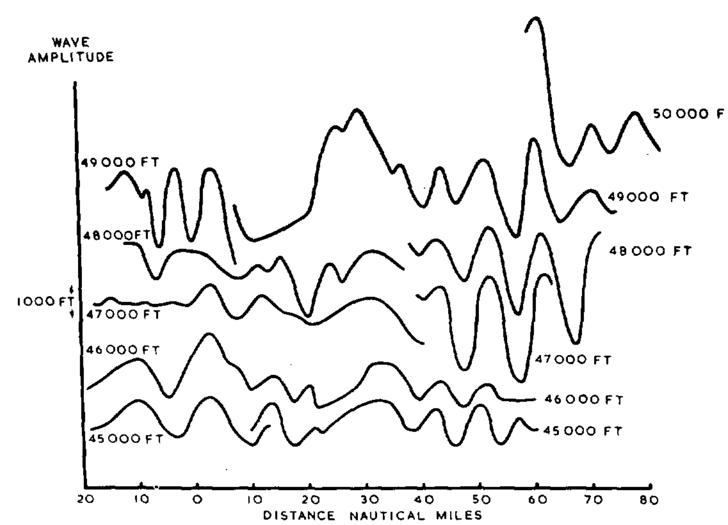

FIGURE 6.—Streamlines of flow in mountain waves over the Western United States, based on constant potential temperature surfaces.

the stratosphere and sometimes even amplify there. During a number of flights in the stratosphere made by the RAE over the western United States together with a Canadian NAE (National Aeronautical Establishment) aircraft that flew near tropopause level, significant disturbances associated with mountain and lee waves were found on several days in the stratosphere when none were apparent near the tropopause. Estimated streamlines for the wave flow on one such day are shown in figure 6. The occasions when significant wave disturbances were found in the stratosphere were associated with the existence of mountain and lee waves in the troposphere together with stable layers (near the altitude of the disturbances) in the stratosphere (fig. 7). An analysis of meteorological data corresponding to the most severe gusts reported in the stratosphere in other studies shows similar stable layers.

Little is known from a climatological point of view about the existence of these stable layers, but it appears that they are uncommon. Their identification with severe wave disturbances in the stratosphere is by no means certain and complete, nor do we know how far they are likely to lead to significant disturbances in the absence of a wave system in the troposphere. Further flight measurements are needed, together with a greater insight into the physical mechanisms involved. It is hoped that basic research on flow in stratified fluids will assist in this process.

At present, some airlines avoid flight through areas in which significant mountain wave activity is forecast in the troposphere. In all known cases of encounters in the stratosphere with a significant mountain wave disturbance, such a forecast would have been made on the basis of current techniques. It therefore seems that mountain waves and their associated disturbances are unlikely to be

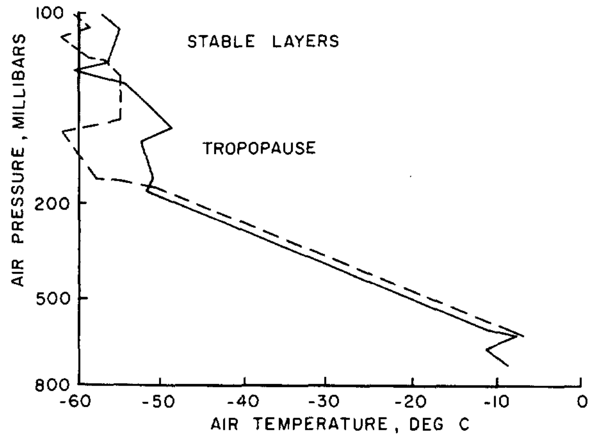

FIGURE 7.—Examples of upper air temperatures showing the existence of stable layers in the stratosphere.

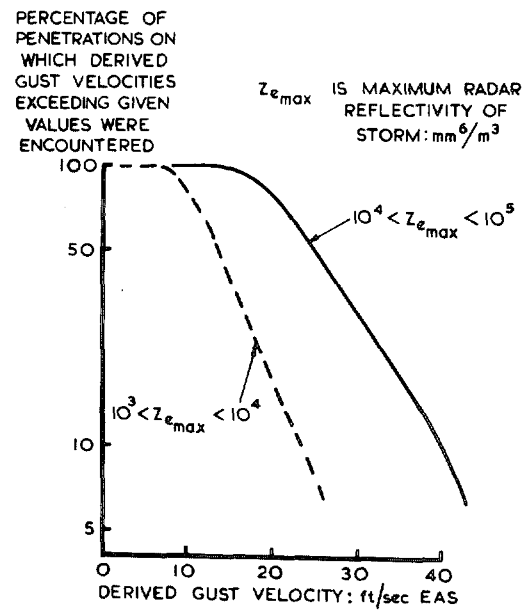

FIGURE 8.—Effect of the maximum radar reflectivity of the storm on the maximum derived gust velocity encountered on thunderstorm penetration.

greater operational problems to a SST than they are to current aircraft.[1]

While the possibility exists that severe disturbances can occur in the stratosphere in other than thunderstorm and mountain wave situations, no reliable reports of them are known. It appears, largely from the results of the USAF HICAT program, that gusts in the stratosphere are less frequent and less severe than at lower altitudes. Nevertheless, HICAT and RAE programs show that, in some parts of the world at certain times of the year, a SST may occasionally spend 10 to 15 percent of its cruise time in turbulence sufficiently intense to be noticeable to the passengers.

4. GUSTS AT ALTITUDES USED BY PRESENT TRANSPORT AIRCRAFT

The predominant part played by thunderstorms in turbulence accidents and incidents involving current transport aircraft has been described in section 2. This has been reflected in RAE studies of gusts in and around thunderstorms at currently used altitudes and of the use of weather radar to avoid them. Much of this work has been done in collaboration with the U.S. National Severe Storms Laboratory (NSSL). Gust measurements in thunderstorms had been made in a number of test series in the United Kingdom and the United States; but with the exception of some NASA (National Aeronautics and Space Administration) measurements made in the early 1960s, no true gust velocity measurements were available. In only a very few cases could the data be compared with quantitative radar measurements of the storms.

The RAE–NSSL work has allowed the relationship between gust intensity and properties of the radar echoes of Oklahoma storms to be firmly established over an altitude range from 23,000 to 35,000 ft (Burnham and Lee 1969). A clear relationship exists between the probability that the largest derived gust velocity encountered on a given storm penetration exceeds a given value and the maximum radar reflectivity of the storm penetrated (fig. 8). Measurements made in convective clouds in the United Kingdom in which derived and true gust velocity[2] statistics were compared and found to be in good agreement (fig. 9) suggest that results similar to those of figure 8 apply also to the true gust velocities. Gust intensity was found to be unrelated to other properties of the radar echoes such as average reflectivity or maximum or average reflectivity gradient. For storms of a given intensity as measured by radar, a higher probability of encountering a large value of derived gust velocity was found on those penetrations that passed through the most reflective part of the storm (that is, its core) than for those that, while still passing through a part of the storm giving an echo on the ground radar used in the tests, missed the core by more than 5 mi (fig. 10). For those aircraft penetrations that passed through storm cores, the design values of derived gust velocity were encountered on approximately 10 percent of the occasions.

The Oklahoma and U.K. results are probably suitable guides to storm turbulence in other parts of the world; further evidence on this point is greatly desirable. Airborne weather radars are not so powerful, so sensitive, or so stable as the ground radar used in the tests. Although available comparisons between airborne and ground weather radars are few, they provide no reason for be-

[1] This comment and a similar one about thunderstorms assume that SSTs will not be much different from current aircraft in the way in which they respond to atmospheric disturbances. This assumption is reasonable for the types of SSTs that we have so far considered.

[2] True gust velocities are actual components of air motion. Derived gust velocities are obtained directly from measurements of incremental normal acceleration, being the size of gust of a particular shape that would have produced that acceleration (see appendix of Burnham and Lee 1969). Derived gust velocities are often quoted in terms of equivalent airspeed (EAS), this being the product of the actual true air velocity (TAS) and the square root of the relative density.

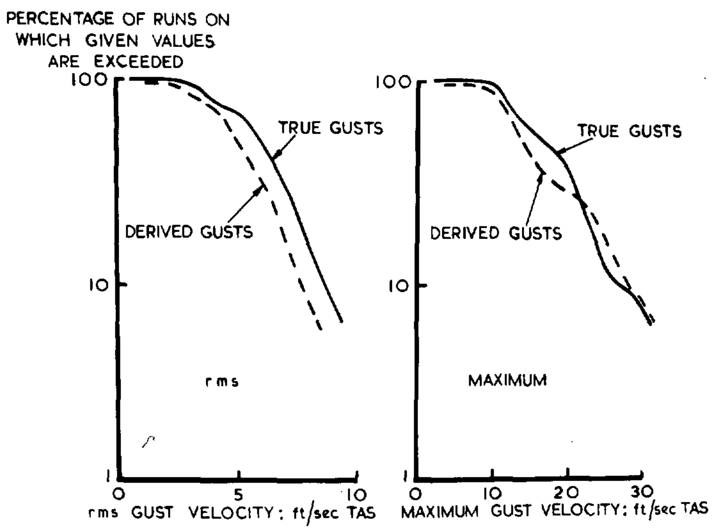

FIGURE 9.—Probabilities of encountering given rms and maximum gust velocities from flights through convective cloud.

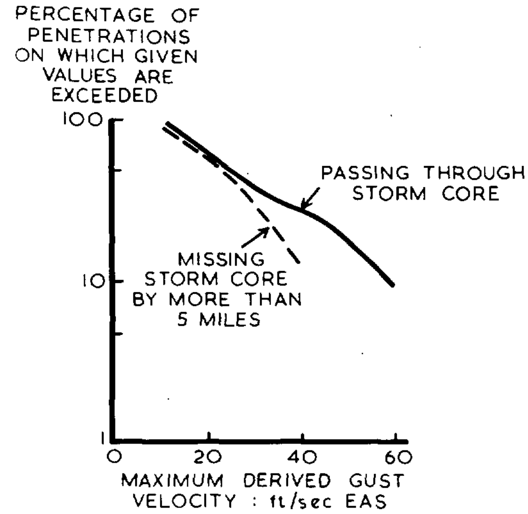

FIGURE 10.—Effect of passing through or missing the storm core on maximum gust velocities encountered on thunderstorm penetrations (at heights between 23,000 and 28,000 ft through storms with maximum reflectivity factors between 10^4 and $10^{5.5}$).

lieving that airborne systems are significantly worse so far as the detection of the positions of storms is concerned. It should be noted that there is a period of a few minutes at the beginning of any storm cell's life when the visible cloud and air motion are present, but there is as yet insufficient liquid water to give a radar echo.

Reference has already been made to the meteorologist's present ability to forecast regions of the troposphere likely to be affected by mountain and lee waves and associated disturbances. These can be severe and have been responsible for at least one catastrophic accident. Although no measurements of severe gusts in tropospheric waves have been attempted by the RAE, some measurements made by a USAF instrumented aircraft in the lee of a high mountain ridge in strong wind conditions have been analyzed and are referred to in section 6.

Although RAE research has concentrated on convective clouds and wave situations in which operationally dangerous gusts are likely, the much more common but less intense CAT is a significant nuisance to airlines and their passengers. The current situation regarding the forecasting of CAT has been described by Jones (1967) as follows: "The present position is, therefore, that we know a great deal about the possible locations of CAT, sufficient to be able to predict general areas where the chance of encountering turbulence is greater than elsewhere. This is possible mainly by identifying the position of the jetstream and predicting its intensification or decay, and its movement . . . . We are not, however, in a position to forecast with certainty where in the general areas, air motion will suddenly break down into turbulence. A great deal more research is required before we can hope to narrow down these areas and give the pilot more precise warnings of rough patches."

In recent years, much effort has been spent, particularly in the United States, in attempts to develop an airborne device that will detect CAT ahead of an aircraft. On the whole, the proponents of the various techniques that have been tried appear to have become less optimistic as time progresses. At present, only one technique appears to have a worthwhile chance of success. This is infrared radiometry used to detect temperature changes ahead of the aircraft, it being hoped that the temperature of the patch of CAT differs from that of the surrounding air. It is known from RAE and Meteorological Office work that this is not always the case, but it is possible that the correlation may improve as the intensity of the CAT increases. If the range discrimination of radiometers can be improved, there is hope that an operationally useful instrument will result.

5. GUSTS IN RELATION TO TAKEOFF AND LANDING

In recent years, there has been considerable interest in the United Kingdom in gust problems in relation to takeoff and landing, particularly in connection with the manual landing of large aircraft and the assessment of the safety of automatic landing systems. Although gusts are likely to be small in the poor visibility conditions for which the latter were originally intended, it is necessary to build up confidence in the system by operation in clear weather, and some operators wish to use these systems in all weather.

Large gusts are, of course, most likely to occur in strong winds and where the terrain is irregular. Since much information on gusts near the ground comes from measurements made on instrumented masts on sites that are flat compared with the neighborhood of most airfields, its applicability to takeoff and landing problems is doubtful. This applies particularly to measurements of vertical gusts at heights below about 200 ft. Much work needs to be done

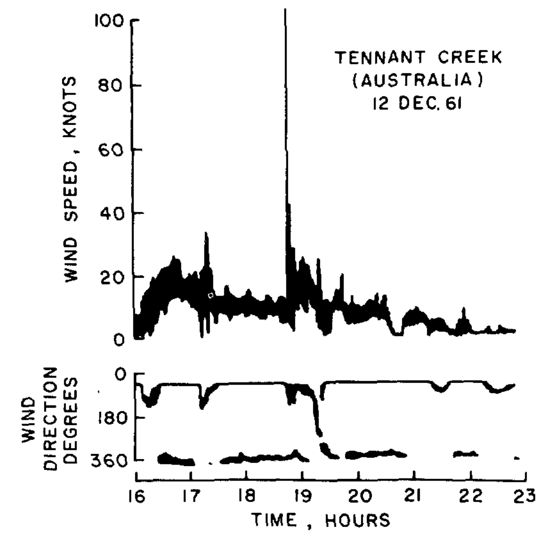

FIGURE 11.—Anemogram of a large squall.

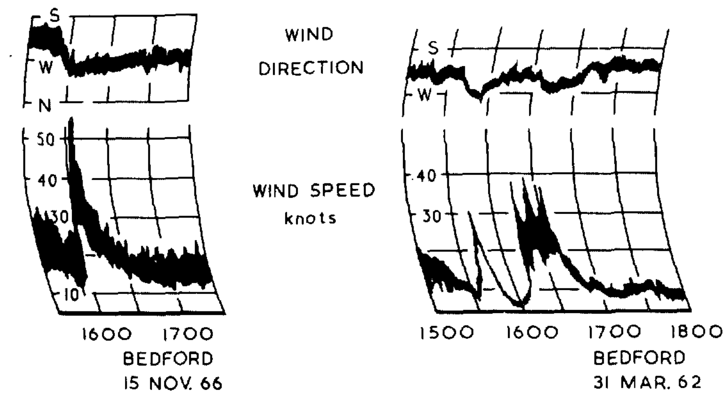

FIGURE 12.—Anemograms of squalls recorded at Bedford, England.

in conditions similar to those of practical interest before conditions can be defined confidently.

From the operational point of view, both for giving a needed improvement in the prediction of the severity of conditions for present day piloted aircraft and for allowing the placing (where necessary) of sensible limits on the conditions in which automatic landing systems may be used, it is essential that the severity of gusts likely to be met on the landing approach be related to general meteorological parameters, or their forecasting be facilitated by some other means.

The importance of wind shear effects (in the sense of wind variations with height that persist for a minute or more) can be much overrated. At altitudes of primary concern to landing safety (below about 200 ft), such shears are likely to break down into turbulent fluctuations that are sensed more by an aircraft than the shear would be. Large shears are much more likely to occur above 200 ft than below; and at these altitudes, the gusts primarily affect glide path performance rather than directly affect landing safety. A system, either human or automatic, that can cope with the average level of gusts likely in a 30- to 40-kt wind is not likely to be greatly troubled by wind shear, except perhaps for the human pilot who is taken by surprise. However, significant shears may be associated with large temperature stratification, and important wave effects may occur occasionally at a few airports.

Large and rapid fluctuations of wind are not confined to situations in which the mean wind preceding them is strong. Large gusts that follow light winds are associated with convection around and above the earth's boundary layer; and larger gusts, which have resulted in a number of accidents, are associated with thunderstorms and are usually referred to as squalls. The anemogram of a particularly horrendous example is shown in figure 11. Smaller troublesome squalls occur relatively frequently in the United Kingdom. The average number per year over the last 5 yr at the RAE at Bedford has been 40. Two examples of these are given in figure 12. A transport-type aircraft was flaring prior to a landing (on a westerly heading) when the squall of Nov. 15, 1966, occurred. The aircraft touched down with a large sideways velocity, but an accident was averted because the runway was wet, allowing the aircraft to slide sideways.

A very large number of squall records are available from the Meteorological Office, but they do not resolve the fluctuations with the accuracy needed to determine their effects. In an attempt to obtain further information, continuous records of windspeed at heights of 30, 50, and 100 ft are being obtained on an expanded time scale using an instrumented tower at the RAE at Bedford. An interesting record of an almost steplike gust obtained with this system is shown in figure 13.

The coming operation of VTOL (verticle takeoff and landing) and STOL (short takeoff and landing) aircraft is likely to lead to new demands for knowledge of the gust environment in urban areas.

6. DESCRIPTION OF GUSTS

GUST SPECTRA

Up to the mid-1950s, the "discrete gust" approach to gust loads was practically universal. In this, gusts are considered to be a fixed and relatively simple shape (a ramp or 1 − cosine function with a fixed length in feet or aircraft chord lengths) and variable amplitude. Although gusts are not really like this, the approach has worked well and is still the primary one used by the aircraft industry.

"Spectral methods" were introduced to gust load studies in the late 1940s, having been used in the fluid mechanical description of turbulence for the previous 20 yr. The gusts are here conceived as examples from a random process with a determine spectral density (average variation of energy with frequency or wavelength). Knowledge of this spectral density with the dynamics of the aircraft (variation of response with input frequency) allows the spectral

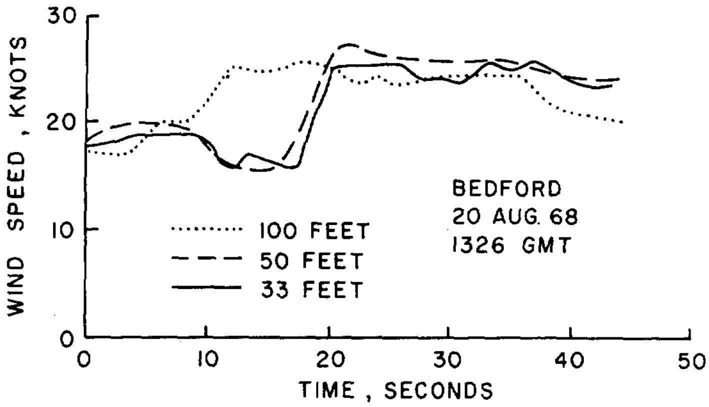

FIGURE 13.—Time history of a rapid change of windspeed.

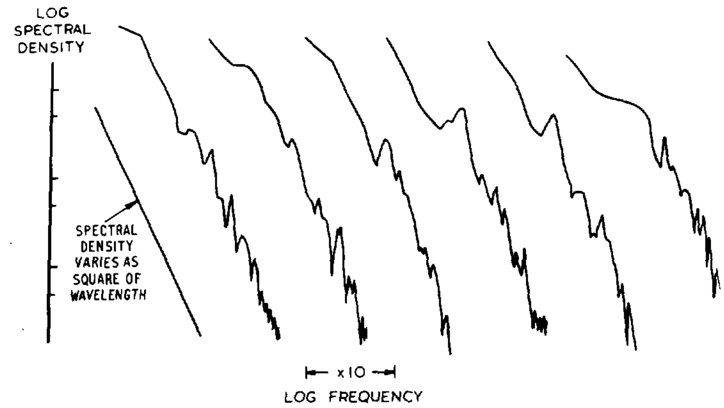

FIGURE 14.—Shapes of spectral densities of true vertical gust velocity measured during flights through thunderstorms.

density of the response to be calculated if the system is linear. Thus rational account could be taken of the effects of aircraft rigid body and aeroelastic dynamics.

If in a homogeneous region of stationary random air turbulence, energy is fed in only at the long wavelengths, Kolmogoroff's well-known result is that the spectral densities of the turbulence components decay as the five-thirds power of wavelength over a range (known as the inertial subrange) from around the shortest wavelength at which energy is being fed in down to wavelengths of a few centimeters where viscous effects begin to predominate. When given the assumptions made, the five-thirds power law is a reflection of the physical properties of air. However, if the turbulence is not homogeneous—for example, if energy is fed in where measurements are made, but the decay takes place somewhere else—a slope steeper than five-thirds would be expected over part of the frequency range. Many examples of spectra measured in this kind of situation show a square law decay, figure 17 for example.

As wavelength increases to values near those at which energy is being fed into the turbulence, the spectral density begins to flatten. The wavelength at which the bend occurs is a measure of the "scale" of the turbulence. Most of the many definitions of scale give its numerical value as effectively proportional to but not equal to this wavelength. The generally used "theoretical" turbulence spectra due to Dryden and von Kármán, for examples, show a fairly abrupt bend and an almost flat spectrum at long wavelengths. The available evidence suggests that in practice the bend is not so abrupt, as indicated in figure 15. Many measured spectra do not show a bend at all, and measurements at the long wavelengths involved are very demanding on instrumentation accuracy. During the last 10 yr, as instrumentation has improved, the generally recommended value of turbulence scale has increased tenfold.

Taking, rather arbitrarily, the Dryden formula and matching the appropriate autocorrelation functions[3] with those measured (fig. 16), turbulence scales ranging from 1,750 to 7,800 ft have been obtained from examples of the vertical component of turbulence measured in clear air near storm tops. Corresponding values inside the thunderstorms range from 750 to 2,300 ft, these being for the spectra shown in figure 14. Some rather unexpected results have recently been obtained by the RAE from measurements of vertical gusts at heights between 50 and 200 ft over Bedford Airfield. These give scales that tended to be greatest at the lower altitude, contrary to expectations, and the numerical value at 50 ft is much longer than was thought likely. While it is not suggested that these few results at low altitudes call for an immediate revision of ideas, more evidence is badly needed from sites of practical interest such as airfields and their approach areas.

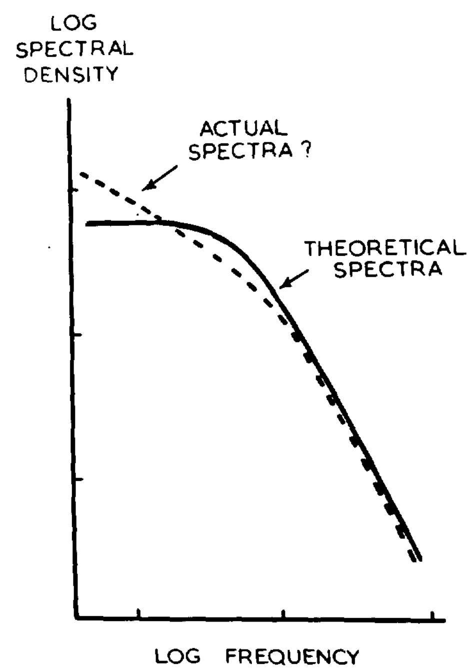

FIGURE 15.—Shape of "theoretical" gust spectra compared with possible shape of actual spectra at long wavelengths.

[3] The autocorrelation and spectral density are Fourier transforms of each other.

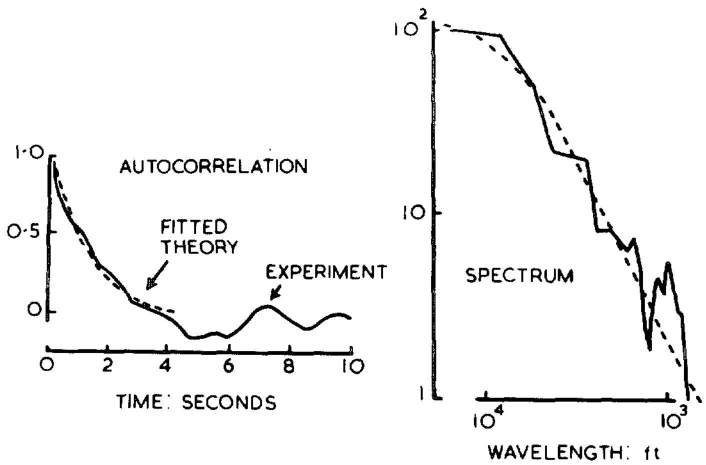

FIGURE 16.—Experimental gust autocorrelation function, fitted theoretical curve, and corresponding spectral densities.

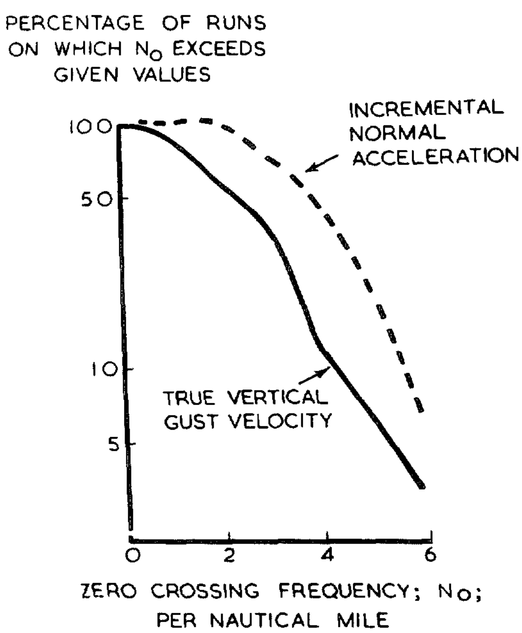

FIGURE 17.—Percentage of runs on which zero crossings of true gust velocity and incremental normal acceleration exceed given values, obtained on flights through convective clouds.

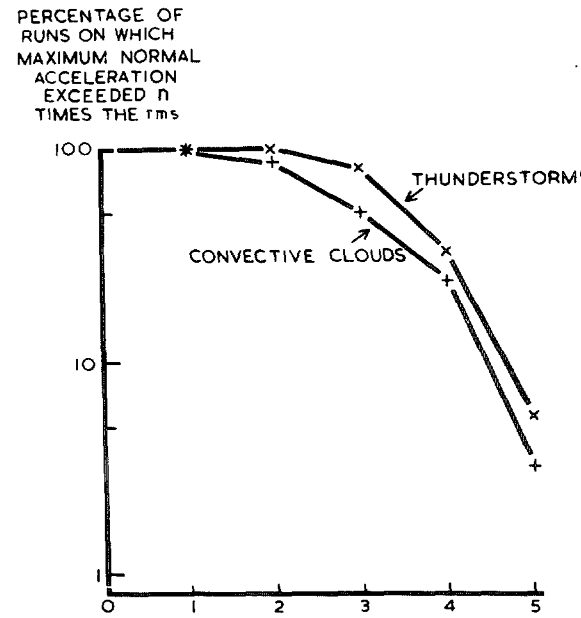

FIGURE 18.—Percentage of runs through convective clouds and thunderstorms on which the maximum normal acceleration exceeds n times the rms.

The spectral densities described above show how, on the average, the energy of the turbulence varies with wavelength. Spectral methods also provide a valuable tool for comparing measured aircraft loads and motions with theoretical predictions. The primary question that concerns the aircraft designer, however, is usually how often a relatively extreme and rare event will occur. The spectral density, alone, will not tell him this.

GUST PROBABILITIES

If gusts were a Gaussian process, knowledge of their spectrum and root-mean-square value would allow any desired probability to be calculated. In particular, if aircraft behaved as linear systems, the average frequencies at which given loads are likely to be exceeded could readily be obtained. Unfortunately, the overall probability distributions of gust loads encountered operationally are nothing like Gaussian. Rather, the large loads are usually a good approximation to an exponential distribution. The usual way around the associated difficulties is to assume that each individual turbulence encounter is with a Gaussian process but that the rms values corresponding to each encounter may be different.

The usual method of calculating the average frequency of a function's zero crossings per unit time from knowledge of its rms and spectrum shape is mathematically correct only if both the function and its first derivative are Gaussian. In this situation, there is good agreement between experiment and theory. However, results obtained on flights through convective clouds, where the probability distributions during individual cloud penetrations do not appear to have been near Gaussian, show wide variations in the zero crossing frequencies of both *cg* normal acceleration and true vertical gust velocity (fig. 17.) The percentage of runs on which the maximum exceeds a given factor times the rms is much greater, in both the convective cloud and thunderstorm flights, than would be obtained with a Gaussian process (fig. 18).

In relation to aircraft response, a property of the true gust velocity that can usefully be considered is the transition function, the change in gust velocity that occurs over a fixed time or distance "lag." The rms of the transition function is usually called the structure function and is uniquely related to the autocovariance, whether or not the process is Gaussian. For a given patch of moderate

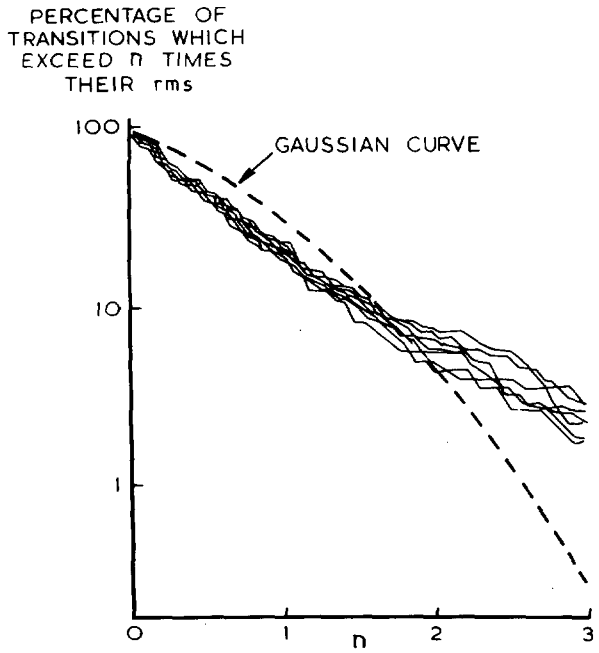

FIGURE 19.—Percentage of transitions with lags of ½, 1, 1½, 2, 3, 4, and 5 min that exceed 7 times their rms from measurements made at a height of 1,458 ft on an instrumented mast.

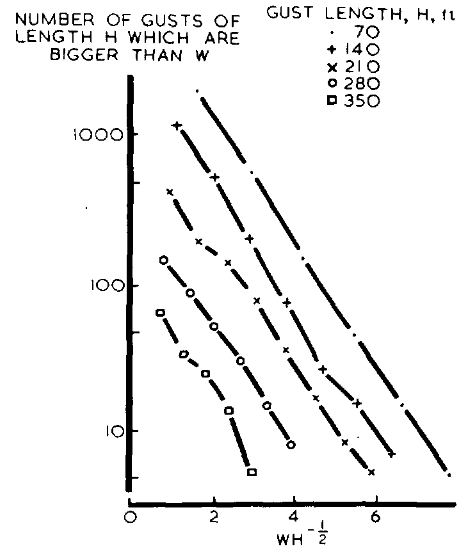

FIGURE 21.—Number of gusts of length H that are greater than W, for gusts in the lee of a mountain range.

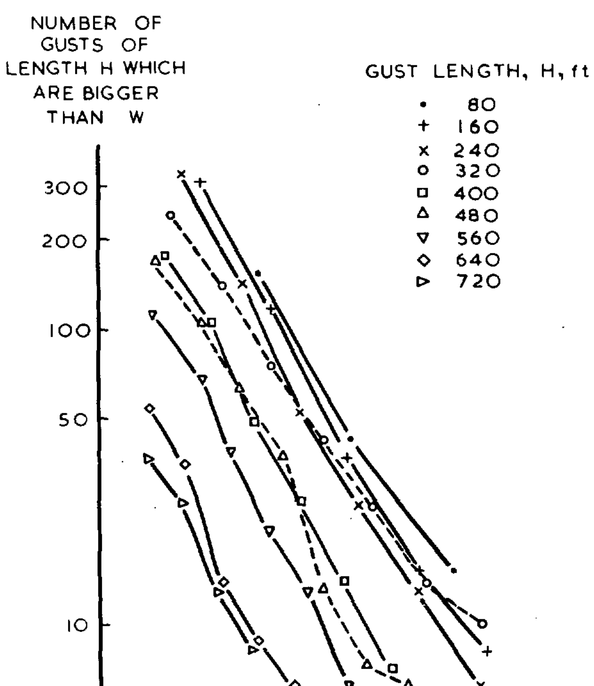

FIGURE 20.—Number of gusts of length H that are greater than W, for thunderstorm data.

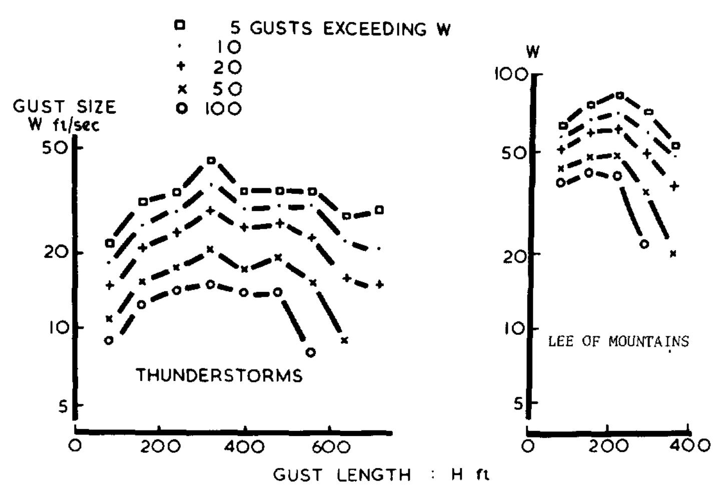

FIGURE 22.—Variation with gust length of the number of gusts of a given size encountered.

or severe turbulence, the probability that transitions in excess of a given value will occur tends to be exponential for values more than about twice the rms in all the examples so far examined and sometimes is close to exponential even for small values, as shown in figure 19.

A more subjective approach to the analysis of large gusts has recently been made. This is an examination of time histories of true vertical gust velocity measured in thunderstorms by the RAE and of some U.S. measurements made immediately in the lee of a mountain range in strong winds. Changes in gust velocity that occurred over given distances were picked out by eye. Any change exceeding the threshold used was considered to be a gust of some length, and gusts of different lengths were not permitted to occur simultaneously. The probability distributions of gusts exceeding a given size were found to be exponential for each gust length. For different sources of gusts, the probability distributions differed from each

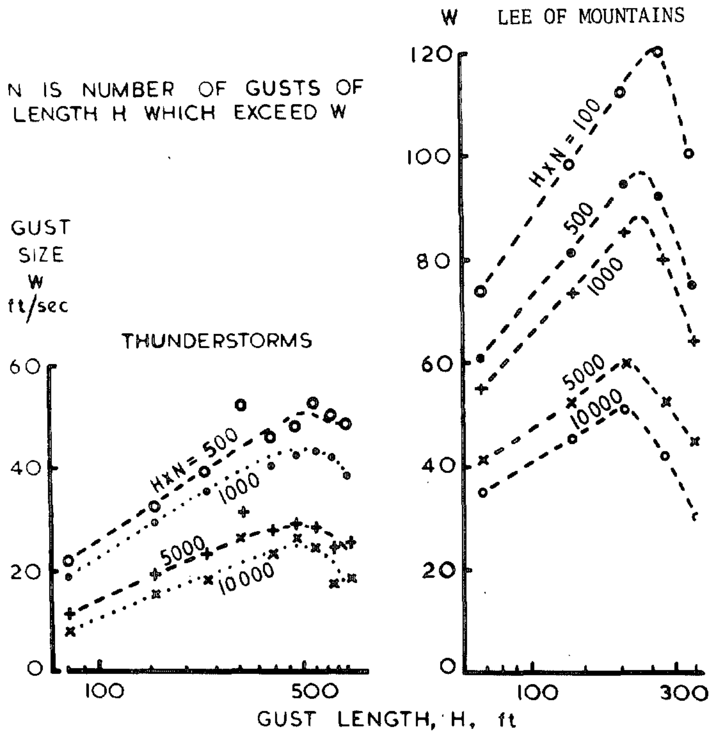

FIGURE 23.—Variation of gust size with gust length for constant values of the product of gust length and the number of gusts of that length exceeding W in size.

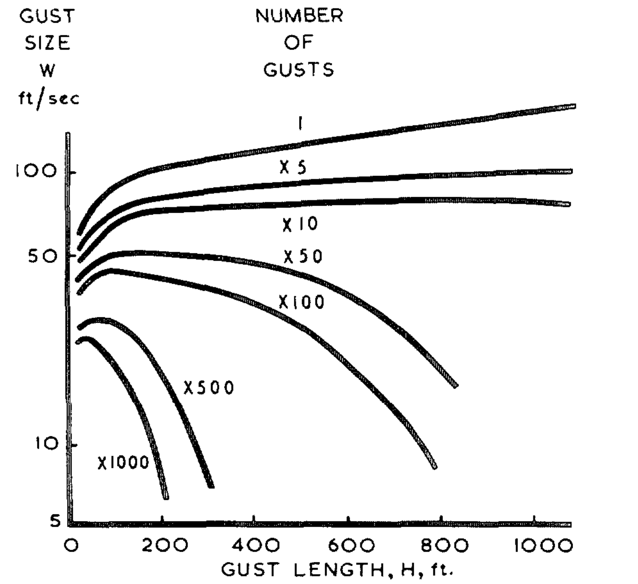

FIGURE 24.—Variation with gust length of a number of gusts of a given size for self-similar gusts with a spectral density that varies as the square of wavelength and exponential probability distribution.

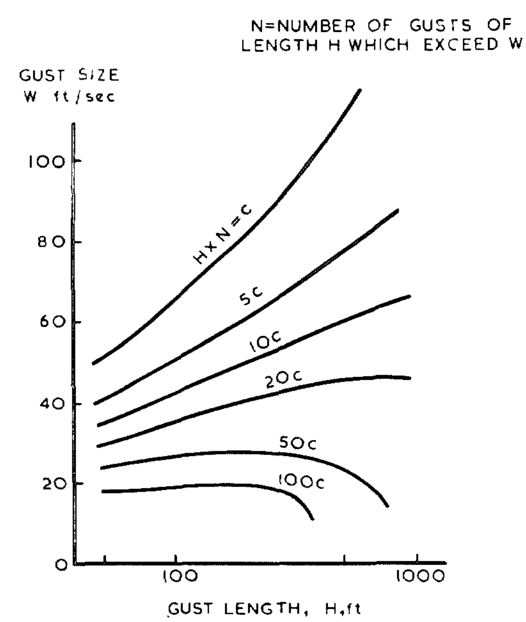

FIGURE 25.—Variation of gust size with gust length for constant values of the product of gust length and the number of gusts of the length that exceed W in size, for self-similar gusts with a spectral density that varies as the square of wavelength and exponential probability distribution.

other by a constant factor when an exponent of gust size divided by the square root of gust length, rather than of gust size itself, was used (as shown in figures 20 and 21). Curves showing the variation with gust length of lines of equal probability of gust velocity exceedance are shown in figure 22. In comparing the behavior of different sizes of aircraft, it is sometimes convenient to consider the behavior of isopleths of the product of the number of gusts exceeding a given size with the gust length, and such curves are shown in figure 23.

A further example of the practical application of the Gaussian assumption concerns the use of synthetic turburlence made with Gaussian noise generators, the output of which is filtered to give the correct spectral density. These have frequently been used in rig testing of automatic flight control systems and in simulators. So far as the prediction of extreme values is concerned, this synthetic turbulence does not have the same properties as the atmosphere.

It is clear that the Gaussian representation of atmospheric gusts, on the whole or as individual patches, lacks physical reality. Nevertheless, spectral techniques based on the Gaussian assumption are a useful advance, from an empirical point of view, on what has gone before. But they are not "rational design methods" based on a physical understanding of atmospheric gusts.

THEORETICAL MODELS OF GUSTS

The above doubts about the validity of Gaussian process representations of turbulence has led to a search for theoretical models that, while utilizing spectral ideas in considering the average distribution of energy with wavelength, have probability characteristics that match those of the real atmosphere. A number of concepts are being studied, including those of the transition function mentioned earlier and of similar intermittent random

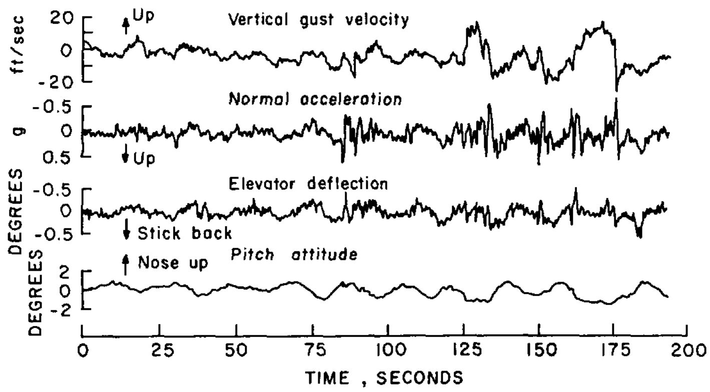

FIGURE 26.—Time histories of true vertical gust velocity, normal acceleration elevator deflection, and pitch attitude measured during flight through a convective cloud.

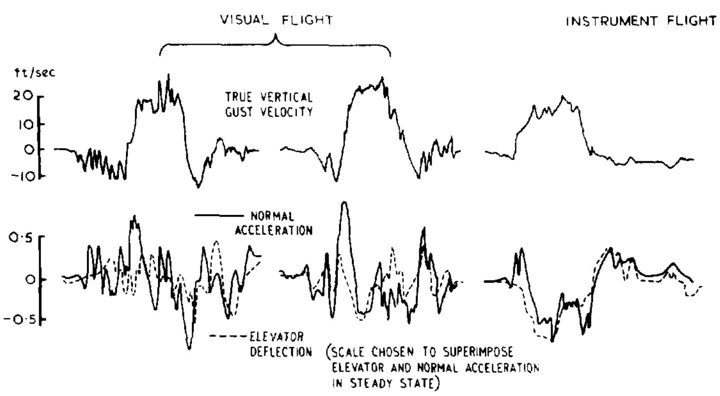

FIGURE 27.—Comparison of incremental *cg* normal acceleration and elevator deflection for instrument and visual flight by the same aircraft and pilot through similar gusts.

processes, and several promising ideas have emerged. This work has been of great value in suggesting ways of looking at severe gust data and of considering such questions as the effect of turbulence scale on the probability properties of the gusts. For example, the equal slopes of the curves on figure 20 from the spectrum shape shown in figure 14 can be predicted. Curves comparable with those of figures 22 and 23 (although the definitions of "gusts" are somewhat different), calculated for self-similar gusts with spectral density varying as the square of wavelength and infinite scale, are shown in figures 24 and 25.

More experimental data on severe gusts, as well as theoretical interpretation, are needed before a physically valid model of them can be put forward for use in design. Good progress is, however, being made toward this end.

7. THE EFFECTS OF PILOT CONTROL ACTIONS ON FLIGHT THROUGH GUSTS

Although the research described above was done primarily to study the gusts themselves, their effects on the test aircraft and crew have also been considered.

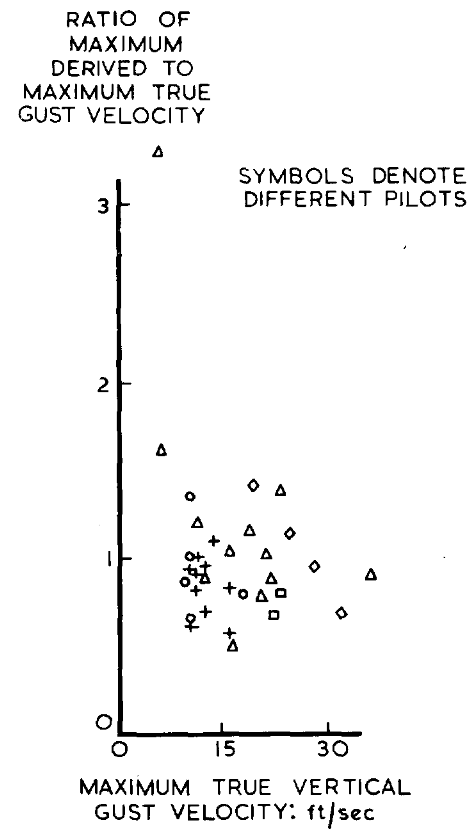

FIGURE 28.—Ratio of rms-derived gust velocity to rms true gust velocity versus rms true gust velocity for flights by different pilots through convective clouds.

Mention was made earlier of a series of gust accidents and incidents known as the jet upsets; similar accidents appear to have happened to propeller-driven aircraft. A feature of the jet upsets was a pitching oscillation with a period of about 20 sec that tended to be divergent, the aircraft finally entering a dive. A similar oscillation (fig. 26) occurred on one of the RAE flights through convective cloud with a fighter aircraft and was damped out only when the pilot regained visual reference.

Comparative studies illustrated by figure 27 show greater control activity in relation to the turbulence level during true instrument conditions than during visual flight, with a strong tendency in IFR (instrument flight rules) flight for the larger accelerations to be closely related to elevator deflection. Figure 28 shows how the ratio of rms-derived gust velocity to rms true gust velocity varies with the true gust velocity for a series of flights with a fighter aircraft through convective cloud. Since the rms-derived gust velocity can be taken as proportional to the rms *cg* normal accelerations, corrected for the effects of height, weight, and speed, figure 28 shows a tendency for pilot control actions to have a decreasingly deleterious effect on accelerations (and so on loads) as gust intensity increases. An unpublished analysis by Zbrożek (RAE) shows a similar effect (fig. 29). However, data on the maximum acceleration experienced on each

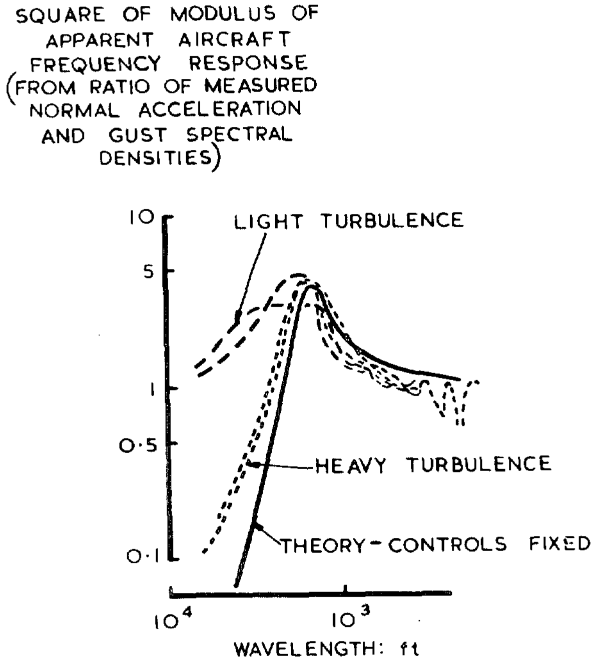

FIGURE 29.—Effect of turbulence intensity on the square of modulus of apparent aircraft frequency response.

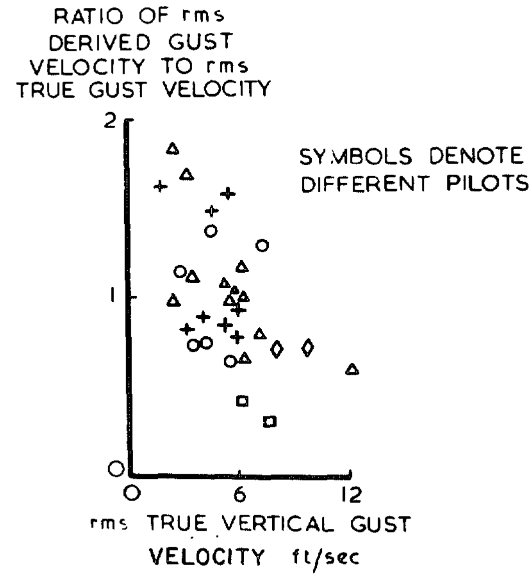

FIGURE 30.—Ratio of maximum-derived gust velocity to maximum true gust velocity versus maximum true gust velocity for flights by different pilots through convective clouds.

cloud penetration indicates that the effect of gust intensity on the ratio of maximum acceleration to maximum true gust velocity is less marked than on the rms (fig. 30).

Operational flight recording data also show that pilot control actions can have a significant effect on the loads experienced during flight through moderate or severe gusts. At the present time, there is no way of taking account of such pilot effects; and in this case, gust load prediction must be an inexact business, however good our knowledge of the atmosphere.

8. CONCLUDING REMARKS

The past few years has seen an increasing concern by those involved in aircraft operations about the effects of atmospheric gusts and the means of avoiding particularly the more severe ones. The great concern expressed in some quarters about CAT appears, in the light of accident and incident data, to be somewhat misplaced. The thunderstorm is still the greatest hazard, but the severe gusts that can occur in mountain wave conditions, long recognized as a hazard by some, are now widely known.

Many airlines have, in recent years, increased efforts in crew training in the use of airborne weather radar for storm avoidance. Although it might be suggested that no great improvements in the radar itself can be foreseen, improvements in the display of information to the pilot are possible. Convincing arguments can be advanced, however, to suggest that airborne radar alone is not always good enough, and a good weather display to the air traffic controller is also needed.

Although no great improvements in gust aspects of weather forecasting seem likely in the immediate future, considerable advances have been made in understanding the physical mechanisms responsible for severe gusts. There are, however, still large gaps in our knowledge. The realization that severe gusts are not just larger versions of the more common less severe ones, but may differ from them in kind as well as in degree, implies that measurements must be made of the severe gusts themselves and so increases the difficulties and dangers of experimental work.

The use of gust statistics such as the spectral density to describe averages from which extreme values may be predicted is a questionable procedure unless adequate regard is paid to other probability properties. There is now clear evidence that the gust probabilities are not Gaussian. Work on theoretical models of extreme gusts that are more physically plausible than those used in the past is showing good progress and should lead to improved design criteria. It has, however, been indicated that account must be taken not only of the gusts but also of the resulting control activity of the human pilot.

REFERENCES

Burnham, J., "Atmospheric Turbulence at the Cruise Altitudes of Supersonic Transport Aircraft," *Progress in Aerospace Sciences*, Pergamon Press, New York, **1970**, pp. 183–234.

Burnham, J., and Lee, J. T., "Thunderstorm Turbulence and Its Relationship to Weather Radar Echoes," *AIAA Journal of Aircraft*, Vol. 6, No. 5, Sept.–Oct. **1969**, pp. 438–445.

Jones, Robert F., "Clear Air Turbulence," *Science Journal*, Vol. 3, No. 2, London, Feb. **1967**, pp. 34–39.

Roach, W. T., "On the Nature of the Summit Areas of Severe Storms in Oklahoma," *Quarterly Journal of the Royal Meteorological Society*, Vol. 93, No. 379, July **1967**, pp. 318–336.

Zbrożek, J. K., "Atmospheric Gusts: Present State of the Art and Further Research," *Journal of the Royal Aeronautical Society*, Vol. 69, No. 649, Jan. **1965**, pp. 27–45.

[*Received October 7, 1969; revised April 15, 1970*]